Quantifying Effects of Mid-Frequency Sonar Transmissions on Fish and Whale Behavior

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LONG-TERM GOALS

There are two high-level goals: to understand and quantify effects of mid-frequency (MF) sonar on fish and whale behavior through direct observation, and to investigate the potential usefulness of MF sonar in acoustic measurements of fish, including stock assessments.

OBJECTIVES

The initial objectives are to prove the usefulness of the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar for observing fish in the water column, and to establish protocols for calibrating the difference-frequency band of this sonar. The TOPAS parametric sonar will then be used as a mid-frequency (MF) sound source, with the aim of collecting data on herring *in situ* in the Norwegian Sea and *ex situ* in pens at the Austevoll Aquaculture Research Station. The data will be analyzed to determine possible behavioral responses of herring to MF sonar transmissions. Ultimately it is the aim to integrate acoustic data on herring with independently collected tagging data from whales to quantify behavioral effects of MF sonar.

APPROACH

This project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting a series of sound-exposure experiments at sea to observe the behavioral response of whales and Atlantic herring (*Clupea harengus*) to mid-frequency (MF) sonar transmissions. The sources of the MF sonar signals are the new, Norwegian, Nansen-class frigate sonar, with operating band 1-8 kHz, and the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar, with primary frequency band 15-21 kHz and difference-frequency band 0.5-6 kHz. The IMR project is entitled "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS.

The approach is intended to augment the Norwegian LowFreq Project in a number of ways. These are arranged by task.

Task 1. Observation of herring by parametric sonar. The PI, K. Foote, is participating on cruises with Norwegian research vessels to observe Norwegian spring-spawning herring *in situ*, especially during

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14. ABSTRACT
There are two high-level goals: to understand and quantify effects of mid-frequency (MF) sonar on fish and whale behavior through direct observation, and to investigate the potential usefulness of MF sonar in acoustic measurements of fish, including stock assessments.

15. SUBJECT TERMS

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the wintering period off the northwest coast of Norway. The first aim of this work is to establish the acoustic detectability of herring with the TOPAS parametric sonar difference-frequency band, which was proposed by the PI to IMR colleagues in 2003. Given measureable echoes, the second aim is to establish the quantifiability of herring by the same difference-frequency band, including measurement of numerical density and sizing based on excitation of swimbladder resonance. The PI will participate in analyses of the data, especially through application of calibration data (Task 2) and developed range compensation functions (Task 3).

Task 2. Development of standard-target calibration protocols for parametric sonar. The PI will lead development of these protocols, already commenced through the design of a standard target for calibration of the difference-frequency band of TOPAS, namely a 280-mm-diameter solid sphere of aluminum alloy (Foote et al. 2007). It is noted that measurement of fish in the upper water column will be made in the TOPAS nearfield, where the difference-frequency wave is being formed, hence the calibration measurements will be made at several ranges. In addition, the high directionality of the difference-frequency wave will require precise target positioning in the transducer beam, which can be accomplished by using an auxiliary sonar operating at an ultrasonic frequency. The PI will participate in the initial calibration trials in the Norwegian Sea, and participate in the analysis of forthcoming data, providing necessary guidelines.

Task 3. Development of range compensation functions for parametric sonar. The PI will develop range compensation functions, called time-varied gain (TVG) functions when applied electronically (Medwin and Clay 1998), for use in measuring the target strength (TS) of resolvable single targets and the volume backscattering strength (S_v) of dense layers of targets, hence of herring in states of relative dispersion and dense aggregation, respectively. Application of range compensation functions aims to remove the range dependence of echoes so that the resulting quantity depends only on the acoustic properties of the targets and their position in the transmit and receive beams of the observing sonar. For conventional sonars, two range compensation functions are particularly useful. For TS measurements, the echo strength in the logarithmic domain is increased by adding the quantity $40 \log r + 2\alpha r$, where r is the target range, typically expressed in meters, and α is the absorption coefficient, typically expressed in decibels per meter. For S_v measurements, the echo strength is increased by adding the quantity $20 \log r + 2\alpha r$. The situation is more complicated for sonars in which measurements are made in the nearfield of the transmit array. This is the case for the TOPAS parametric sonar when applied to fish in the upper water column, for the difference-frequency signal is literally being formed at ranges where backscattering is being measured. It is noted that significant TOPAS echoes are invariably received in the farfield of the transducer array used for reception.

Task 4. Use of parametric sonar as a sound source in the MF sonar band. The PI will participate in cruises to observe the behavior of herring *in situ* during the wintering period and *ex situ* in pens to determine the possible presence and magnitude of effects due to the exposure of the herring to MF sound generated by the TOPAS parametric sonar. The PI will participate in analyses of the *in situ* data.

Task 5. Integration of parametric sonar data on herring behavior with other sound exposure data on herring and whale behavior. When other sound-exposure data become available, the PI will participate in the integration of the TOPAS parametric sonar data in an assessment of the overall effects of MF sound on fish and whale behavior. The other sound-exposure data are expected to include measurements made with the new, Norwegian frigate sonar, and observations derived from tags attached to whales in areas where the whales are feeding on fish.

WORK COMPLETED

Task 1: Atlantic herring were observed *in situ* with the difference-frequency band of the TOPAS parametric sonar on 7 December 2008 during a cruise with R/V "G. O. Sars" in the wintering area off the northwest coast of Norway. The herring were observed in the vicinity of (71 25'N, 16 22'E) in a layer several hundred meters thick in water of approximate 800-m depth. The observations were repeated with the vessel drifting freely and steaming at the ordinary survey speed of 10 knots. The Simrad EK60 scientific echo sounder was operated synchronously at times, with concurrent observations at 18, 38, 70, 120, 200, and 400 kHz. The observations with the TOPAS parametric sonar were made with a variety of signals, including bursts of continuous waves at 2, 3, 4, 5, and 6 kHz difference frequency; Ricker pulses; and linear frequency-modulated (FM) chirp signals, with bandwidths of 2-6 kHz, among others. The herring were sampled by pelagic trawl, confirming the dominance of herring and giving detailed information on their size distribution. This is the first time that fish have been observed *in situ* with a parametric sonar.

Task 2: Calibration trials were conducted with R/V "G. O. Sars" in the Sørfolla fjord, near (67 31'N, 15 24'E), on 10 December 2008, and with R/V "H. U. Sverdrup II" at Haakonsvern near Bergen on 11 December 2008. In both cases the standard target was a 280-mm-diameter sphere composed of the aluminum alloy 6082-T6, made by Kongsberg AS according to the mentioned specification (Foote et al. 2007). During the calibration trial with R/V "G. O. Sars," with near-horizontal hull-mounting of the TOPAS transducer, the standard target was suspended successively at ranges of 90, 225, and 330 m. The target was observed simultaneously with the Simrad EK60/38-kHz scientific echo sounder in a six-frequency configuration, with proximate transducers and split-beam capability at 38 kHz for target positioning.

Task 3: The first range compensation function to be developed for use with the TOPAS parametric sonar applies to measurement of the volume backscattering strength (S_v), since this is used in echo integration, the most widely used method of measuring fish density acoustically. The aim of this is to enable an S_v-measurement to be made independently of target range. Because measurements of fish in the upper several hundred meters of the water column are in the nearfield of the virtual endfire source array (Westervelt 1963, Foote 2007), the range compensation function must consider both the change in on-axis sound pressure level with increasing range and change in beamwidth with range. It is noted that the transmit sound pressure amplitude decreases slower than 1/r for increasing range r, and the beamwidth decreases with increasing range. Computations of beam patterns, beamwidths, sound pressure levels, and apparent source levels were performed with the Convol5 FORTRAN program (Moffett 2003), which is based on previously published algorithms (Mellon and Moffett 1978, Moffett and Mellon 1981). The particular computations assume that the transmit array is effectively a rectangular piston of dimensions 1100x1035 m in the respective alongship and athwartship directions, and that the receive array is effectively rectangular, with corresponding dimensions 262.4x1035 mm.

Task 4: The TOPAS parametric sonar mounted on board R/V "H. U. Sverdrup II" was used as a source of MF sound in exposure experiments conducted on penned herring at the Austevoll Aquaculture Research Station on 12 December 2008. The TOPAS transducer array was mechanically rotated from the vertically downwards orientation to the near-horizontal orientation. Penned herring were exposed to parametric sonar transmissions with difference frequencies over the approximate band 1-6 kHz, while the herring behavior was monitored by observers at the pen. Strong refractive effects were present, and problems with instrumentation in the pens rather diminished the value of these initial observations. Deteriorating weather forced an early termination of the cruise.

RESULTS

Atlantic herring in the stock of Norwegian spring-spawning herring were observed in their wintering area off the northwest coast of Norway with the MF difference-frequency band of the TOPAS PS18 parametric sonar on 7 December 2008. A set of three echograms collected simultaneously with the EK60/18- and 38-kHz scientific echo sounders and TOPAS parametric sonar are shown in Fig. 1 (Godø et al. 2009). It is noted that the first two display the volume backscattering strength, while the TOPAS data are shown in raw units without adjustment for calibration and without range compensation. This is the first time that fish echoes have been measured *in situ* by parametric sonar.

The first standard-target calibration of a parametric sonar was performed in Sørfolla fjord on 10 December 2008. Echoes were registered in the difference-frequency band of the TOPAS parametric sonar at each of three target ranges: 90, 225, and 330 m (Foote et al. 2009). An image of the wetted standard target being deployed by three-point suspension using vessel cranes is shown in Fig. 2. This also contains an image of echo waveforms spanning part of the TOPAS parametric sonar difference-frequency band, 2-6 kHz.

Computational results contributing to derivation of the range compensation function for determining the volume backscattering strength for the difference-frequency band of the TOPAS PS18 parametric sonar are shown in Figs. 3-6 (Foote 2009). These computations and results are preliminary.

IMPACT AND APPLICATIONS

National Security
Navy operations at sea can be affected by the presence of marine mammals. It is expected that the results of the project will contribute to knowledge of possible effects of MF sonar transmissions on the behavior of whales as well as that of other marine animals, especially including fish.

Economic Development
More general use of MF sonars encompassing both water-column and sub-bottom domains may encourage the application, hence increased production, of such sonars. Parametric sonars are especially attractive in this regard because of their physical compactness relative to the exceptionally narrow beamwidths that they produce at low frequencies.

Quality of Life
Society is concerned about the impact of sonar on marine life. This project is attempting to learn about this impact in a quantitative way, ultimately so that possible adverse effects can be avoided or otherwise mitigated.

Science Education and Communication
Forthcoming results from this project are already being published through the scientific literature and lectures to the public. It is expected that these and other publication and communication activities will contribute to science education, as through academic programs in marine science, as well as to more general science literacy among the interested public.

RELATED PROJECTS

As mentioned in the approach section above, this project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting the project “Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq),” with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS. It is expected that the Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the ONR project in disseminating forthcoming results.

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K. G. Foote, “Range compensation function for echo integration in transducer near fields, with special reference to parametric sonar,” J. Acoust. Soc. Am., 125, 2718 (2009) (A)

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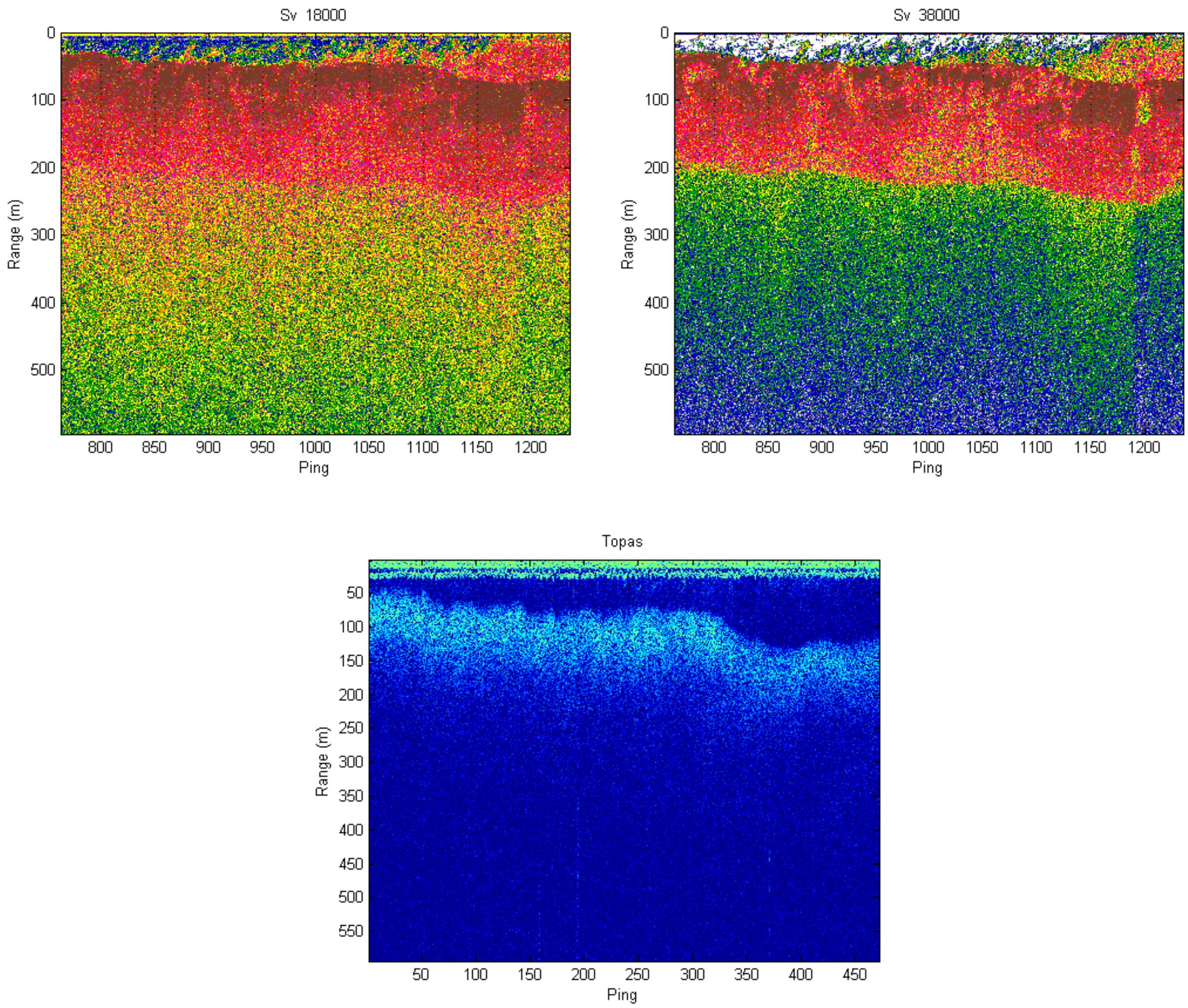


Fig. 1. Three concurrent echograms of Norwegian spring-spawning herring in its wintering area in the vicinity of (71 25'N, 16 22'E) observed from R/V "G. O. Sars" while drifting freely on 7 December 2008. The echograms were obtained with the EK60 scientific echo sounder operating at 18 kHz (upper left panel), 38 kHz (upper right panel), and the difference-frequency band of the Kongsberg TOPAS PS sub-bottom profiling parametric sonar, with transmit chirp signal, band 1-6 kHz, duration 16 ms (lower panel), each with vertically downwards oriented beam. Values of volume backscattering strength are displayed in the EK60 echograms, with stronger values in red and weaker values in blue. Data values in the TOPAS echogram are raw, without range compensation. Credit: J. Dybedal, O. R. Godø, K. Foote.

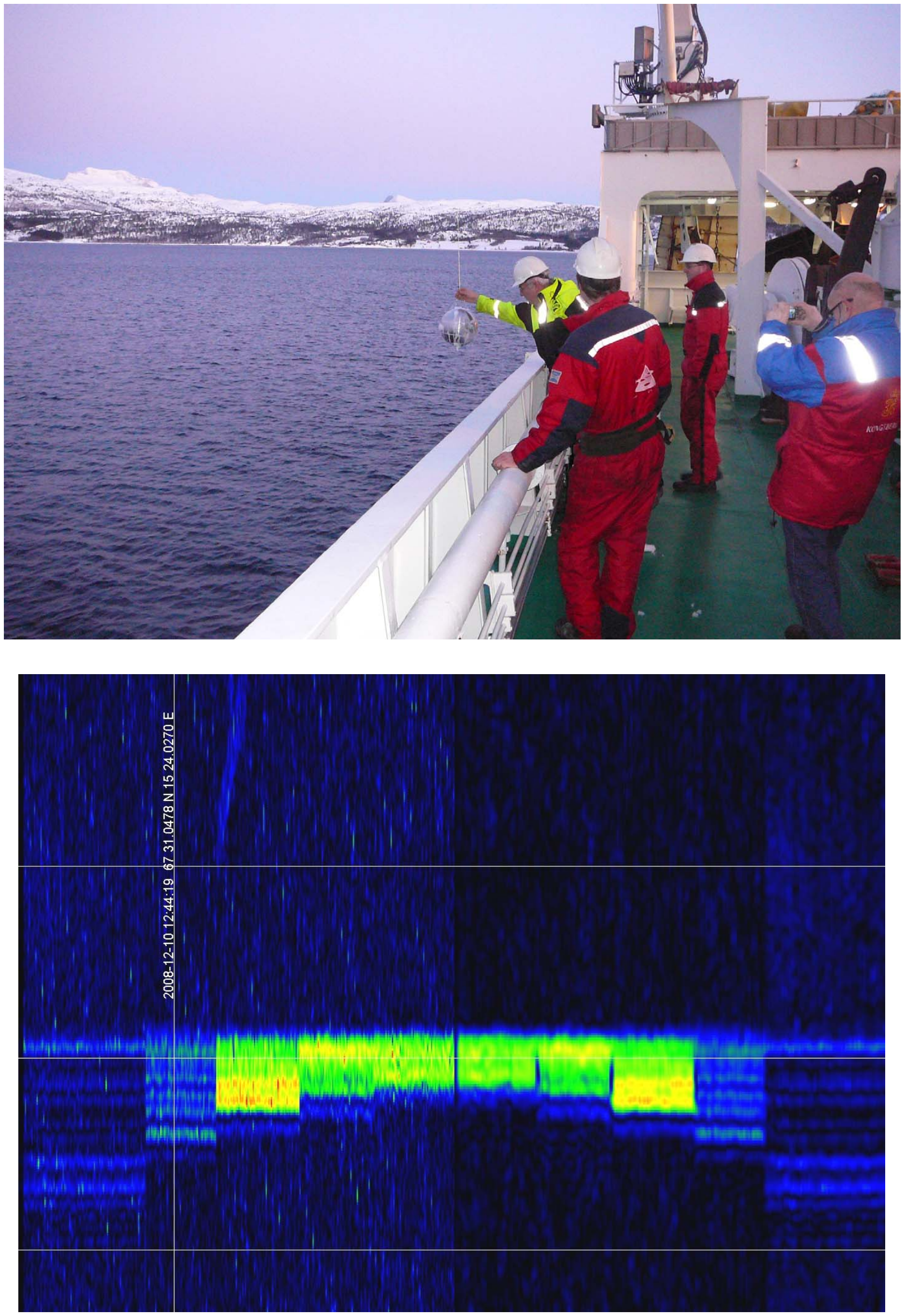


Fig. 2. Deployment of the 280-mm-diameter standard target, composed of an aluminum alloy, wetted by a surfactant, from the aft deck of R/V "G. O. Sars" in Sørfolla fjord on 10 December 2008 (upper panel), used for calibration of the difference-frequency band of the TOPAS PS18 parametric sonar. Composite echograms of measurements of the standard target with the TOPAS PS18 parametric sonar for four-cycle continuous-wave signals at 2, 3, 4, 5, and 6 kHz (lower panel): arranged in order of increasing frequency for single echoes in the left half of the panel and in order of decreasing frequency for five-ping averages in the right half of the panel, hence symmetrically with respect to the single echoes in the left half. Credit: T. Torkelsen, O. R. Godø (upper panel); J. Dybedal, E. Tenningen, R. Patel, O. R. Godø, K. Foote (lower panel).

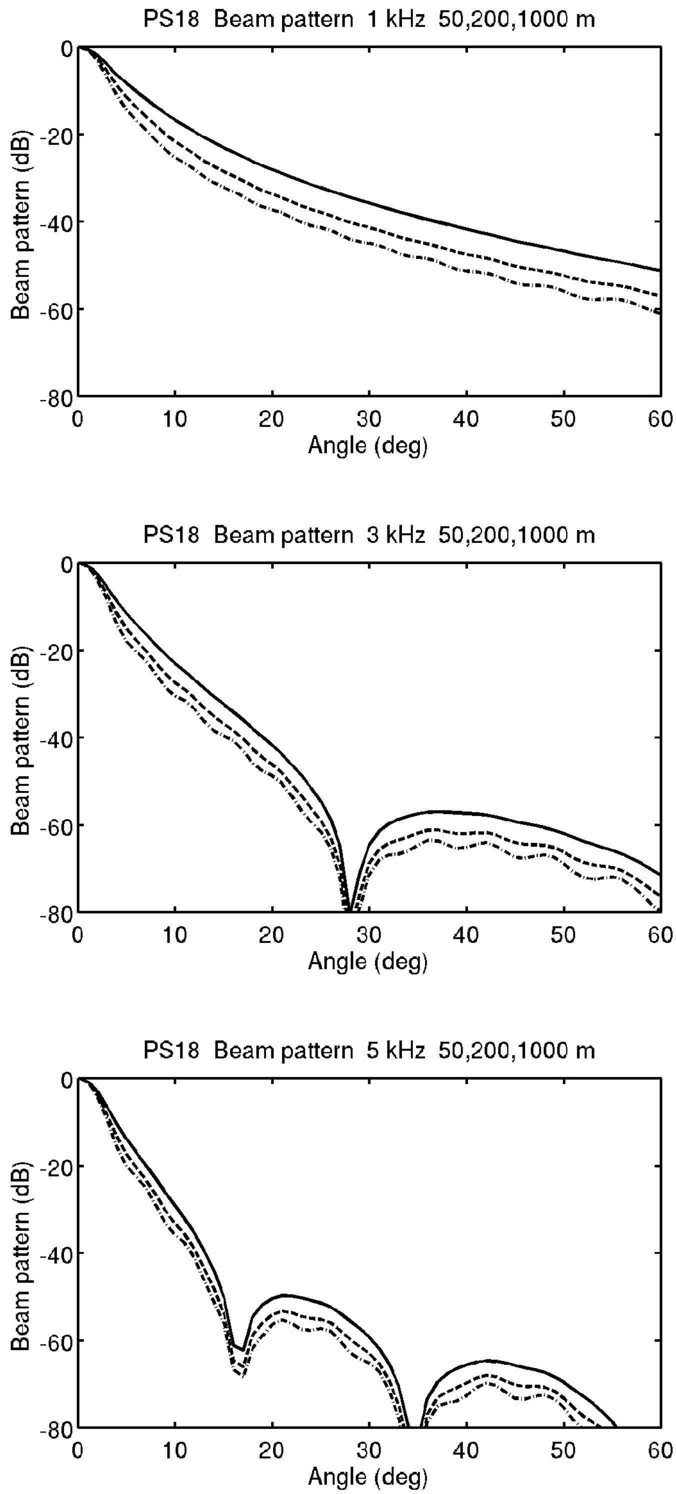


Fig. 3. Transmit beam patterns of the TOPAS PS18 parametric sonar computed in the athwartships plane at each of three difference frequencies, 1, 3, and 5 kHz, at each of three ranges, 50, 200, and 1000 m, determined by exercise of the computer program Convol5 (Moffett 2003) on the basis of TOPAS specifications (J. Dybedal). Credit: K. Foote.

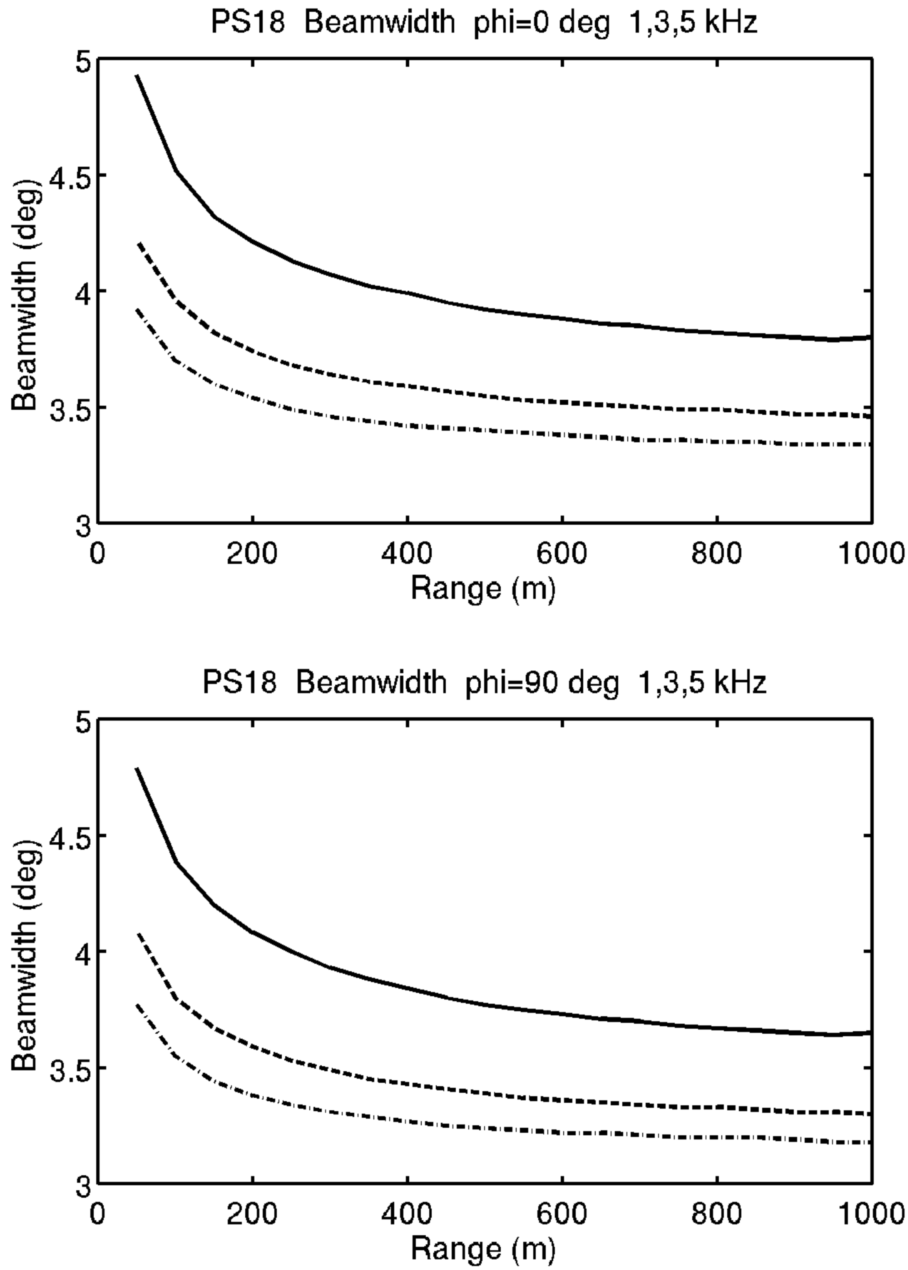


Fig. 4. Range dependence of beamwidths of the TOPAS PS18 parametric sonar computed in each of two planes: athwartships (upper panel) and alongships (lower panel) at each of three frequencies, 1, 3, and 5 kHz, determined by exercise of the computer program Convol5 (Moffett 2003) on the basis of TOPAS specifications (J. Dybedal). Credit: K. Foote.

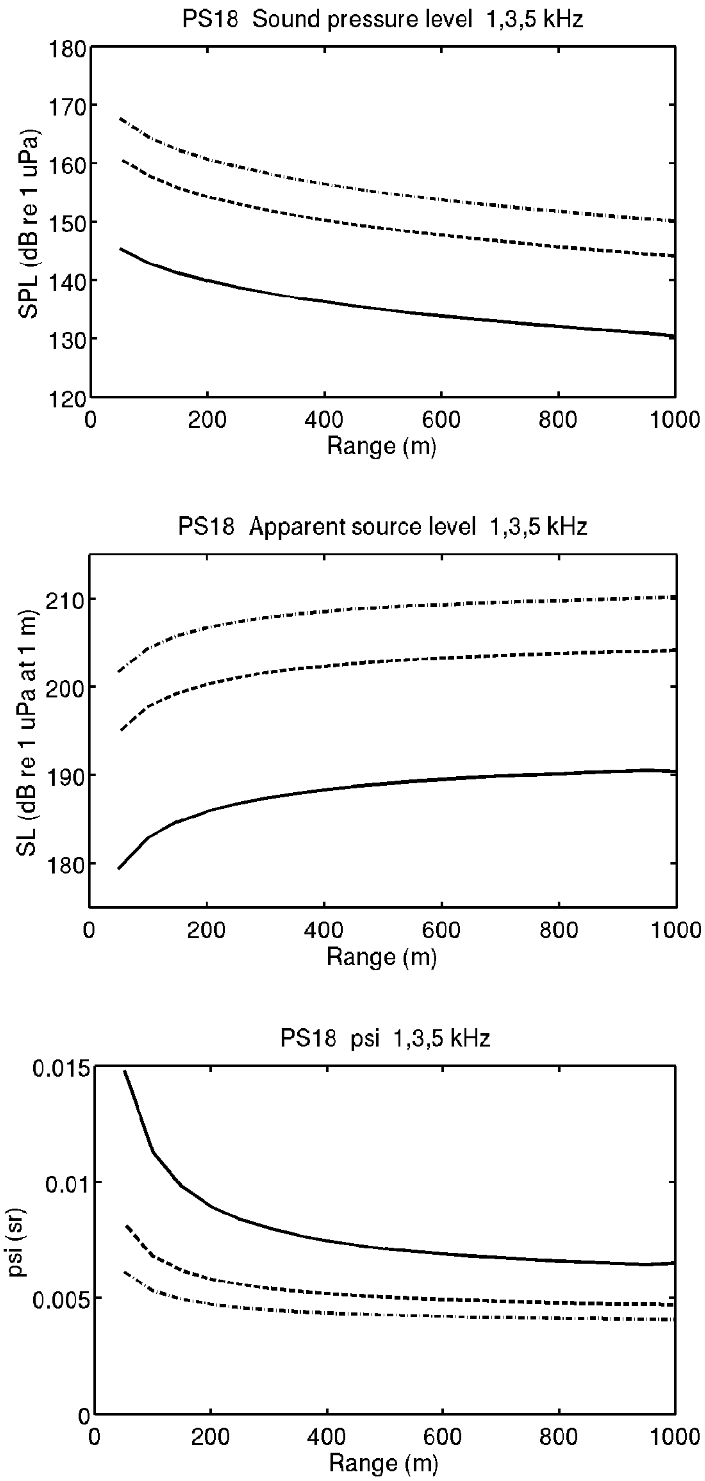
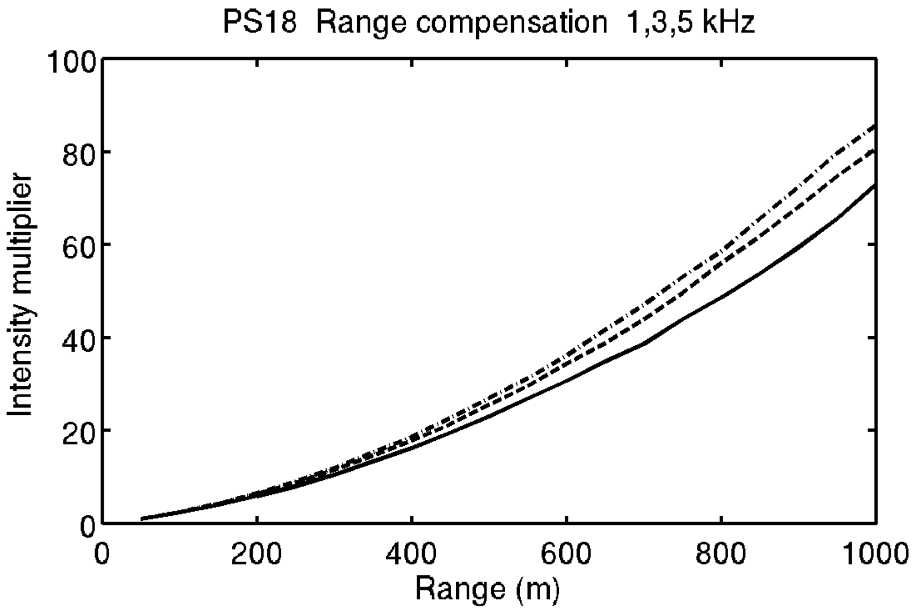


Fig. 5. Range dependence of the sound pressure level (upper panel), apparent source level (middle panel), and two-way equivalent beam angle (lower panel) of the TOPAS PS18 parametric sonar computed at each of three frequencies, 1, 3, and 5 kHz, determined by exercise of the computer program Convol5 (Moffett 2003) on the basis of TOPAS specifications (J. Dybedal).
Credit: K. Foote.



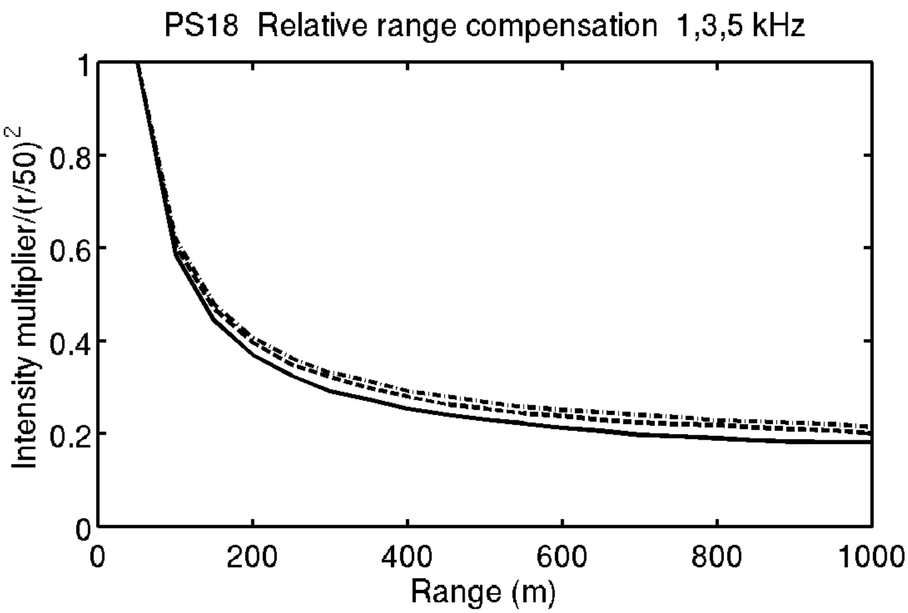


Fig. 6. Range compensation function in the intensity domain for conversion of TOPAS PS18 parametric sonar data to values of volume backscattering strength (upper panel), computed at 50-m range intervals and expressed relative to the value at 50 m, for each of three frequencies, 1, 3, and 5 kHz. The same range compensation function compared to the corresponding range compensation function for conventional sonar data (lower panel). Credit: K. Foote.